International Journal of Modern Physics C, Vol. 0, No. 0 (1993) 000–000
© World Scientific Publishing Company

arXiv:adap-org/9705001v1 4 May 1997

INDIVIDUAL ADAPTION IN A PATH-BASED SIMULATION OF THE FREEWAY NETWORK OF NORTHRHINE-WESTFALIA

KAI NAGEL

Los Alamos National Laboratory, Technology and Safety Assessment Division/Simulation Applications, Mail Stop M997, Los Alamos NM 87545, U.S.A., kai@lanl.gov

and

Santa Fe Institute, 1399 Hyde Park Road, Santa Fe NM 87501, U.S.A., kai@santafe.edu

Received (received date)
Revised (revised date)

Traffic simulations are made more realistic by giving individual drivers intentions, i.e. an idea of where they want to go. One possible implementation of this idea is to give each driver an exact pre-computed path, that is, a sequence of roads this driver wants to follow. This paper shows, in a realistic road network, how repeated simulations can be used so that drivers can explore different paths, and how macroscopic quantities such as locations of jams or network throughput change as a result of this.

Keywords: traffic; adaption

1. Introduction

It is by now clear that large-scale microsimulations of transportation systems, with simulation speeds of 1 millions or more vehicles in real time, are possible.[1,2,3,4,5] It is less clear how to "drive" these simulations, i.e. according to which rules the individual vehicles know where they are headed.

Random turning choices at intersections, as they would probably be favored by the Statistical Physics community, do not work well: They are already unable to represent a simple situation where the traffic in, say, North-South direction is more important than traffic in the other directions.

Traffic science traditionally uses turning percentages (see, e.g., Ref. [6]), i.e. a table for each direction of each intersection which says which fraction of vehicles would go left, straight, right, etc. Apart from the problem of how to collect all the necessary data from the real world, this is only useful for representing the status quo, but useless if one wants to study changes in the transportation system, because the turning percentages change immediately.

The only way out seems to give individual drivers intentions, i.e. an idea of where they want to go. One possible implementation of this idea is to give each driver an exact pre-computed "plan", i.e. a sequence of roads this driver wants to follow.[7,3] See, e.g., Refs. [8,9] for an alternative method.

Pre-computed trip plans do not allow an adjustment during the trip. To make up for this, the simulation can be run several times (periods/days), and simulated drivers can make different choices each day, until they settle down on a choice which is favorable for them. This seems to be a reasonable approach for recurrent (e.g. rush-hour) congestion.[10,11,12]

This paper describes such a simulation using the freeway network of the German Land Northrhine-Westfalia (NRW). There are many travelers with different origin-destination pairs. Travelers have route plans (paths) so that they know on which intersections they have to make turns in order to reach their destinations. In the simulation setup described in this paper, each traveler has a choice between 10 different paths. Each traveler chooses a path, the microsimulation is executed according to the plans of each traveler (no re-planning during the trip), and each traveler remembers the performance of his/her option.

Each traveler tries each option once. Afterwards, she usually chooses the option which performed best in the past, except that, with a small probability p_{other}, another option is chosen randomly, in order to update the information about these other options.

This approach—giving each agent a set of options and let each agent act on the basis of the performances of these options—is a simplified version of Holland's classifier systems.[13] See Ref. [14] for an application of these ideas in an economic context; and Refs. [16,15] for their use in much simpler transportation problems.

Section 2 describes the digital road network used for the simulations; section 3 describes in detail the simulation setup. Section 4 describes simulation results for the adaption scheme; section 5 discusses several variations of the basic simulation to demonstrate the robustness of the results. Section 6 shows, as one measure of effectiveness, the number of vehicles which reach their destination as a function of time. Maybe counter-intuitively, after everybody has settled down on a choice of path convenient for her*self*, the overall network throughput is lower than when everybody just drives the geometrically shortest path. A discussion concludes the paper.

2. Network

The simulations are based on a digital version of the freeway network of NRW, where some lower level highways (Bundesstraßen) are added in order to prevent free ends inside the network. The code is written for parallel computers using message passing, in principle for an arbitrary numbers of computational nodes (CPNs). In practice, two Sparc10 workstations, coupled via optical link and using PVM 3.2, were used. This indicates that experiments such as the one presented in this paper are already possible with a still modest amount of hardware, and that the consistent use of parallel supercomputers will allow systematic analysis of much larger systems.

The network data which is used comes from Rickert,[2] (see also Ref. [3]) as an intermediate step of his input data preparation. The original data is a list of nodes and a list of edges, where the list of nodes contains all ramps, junctions, and inter-

sections, and edges are the connecting segments. In a first step, Rickert deletes all nodes of degree two (e.g. ramps). The resulting network is then distributed on the two workstations. The heuristic used for this simply cuts the network in east-west direction such that the computational load on both workstations is approximately the same. For details see Refs. [2,3,17].

Apart from the network and the individual trip plans, the simulation is kept as simple and straightforward as possible. This includes oversimplified ramps (see [16]) and single directional lanes, i.e. one lane in each direction. The point of this paper is to show the application of simulated individual decision making in a simplified transportation context; a more realistic large scale, path following traffic simulation is for example documented in Ref. [3].

3. Specific simulation setup

A simulation run consists of a *simulation initialization* and *daily iterations.* During the *simulation initialization*, at each boundary segment 2000 vehicles are queued up to enter the simulation. (Boundary segments are all segments which lead through the border of NRW and which are thus connected to the rest of the network only at one end.) Each car randomly chooses a destination, which is one of the other boundary segments. The probability to choose a certain destination is proportional to the fourth power of the Cartesian distance between the origin and the destination segment: $P(destination) \propto (distance)^4$. Obviously, taking the fourth power biases this selection towards long trips. Still during simulation initialization, each vehicle gets a list of 10 different paths to reach its destination. These lists have been pre-calculated for all occurring origin-destination pairs, and contain the 10 geometrically shortest paths which do not use the same node twice.[18–20]

After this general simulation initialization, the *daily iterations* are started. Each daily iteration consists of a *preparation phase* and a *traffic microsimulation phase.*

During each daily *preparation phase*, each vehicle individually decides which path to use. In the first day, each vehicle uses the shortest path; during the subsequent nine days, each vehicle randomly selects one of the not yet tested options. Starting at day 10, it usually selects, as mentioned in the introduction, the option with the best remembered performance (i.e. with the lowest t_{arriv} as defined below). Sometimes, with probability $p_{other} = 5\%$, it selects one of the other options to re-test it.

Now, the *traffic microsimulation phase* of the daily traffic dynamics starts. Vehicles are updated according to the Nagel-Schreckenberg driving logic,[21,22] and they change segments when they are at a junction or an intersection. Each vehicle follows its plan until it reaches its destination segment, and when it reaches the end of that segment, it notes the arrival time t_{arriv}, i.e. the current iteration step of the simulation, which is used as performance criterion for this specific path.

After all vehicles have reached their destinations and recorded the above information, the next day is started, where all vehicles have the same initial position and the same destination as before, but may choose, in the daily preparation phase,

Fig. 1. Situation after 400 iterations (top) and after 1400 iterations (bottom).

Fig. 2. *Top:* Situation at the "first day" after 6000 iterations (100 minutes), when trips through the network are chosen with a fourth order preference for long trips, and when all drivers follow the geometrically shortest path. — *Bottom:* Situation at "day 15" after 6000 iterations (100 minutes), for the same initial conditions as for the top figure, but where drivers have "learned".

a different path according to the adaption rules described above.

4. Adaption results

Fig. 1 shows an example of a simulation after 400 and 1400 seconds. One clearly sees how the initially empty network is filled by vehicles coming in from the boundary nodes. Each pixel in the plot corresponds to a small region of 30 sites (225 m). Gray dots denote that there is at least one car in the region, gray stars mark slightly overcritical regions, where at least one car has velocity zero, and black triangles mark jams: The density here is above 0.4.

Fig. 2 demonstrates the result of the learning algorithm. Both the top and the bottom graph use exactly the same initial configuration of cars with their individual destinations. Both graphs are snapshots of the situation after 6000 seconds (100 minutes). The top figure shows the situation when every driver follows the geometrically shortest path. The bottom figure shows the situation on day 15, when drivers act according to their previous experiences, i.e. they usually use the path where they were fastest in the past. Note some important differences between the figures (the geographical names are shown in the figures):

- Drivers learn to use A43 from Wuppertal through the Ruhrgebiet. A43 is not contained in any shortest long-distance path.
- Around Köln, after the learning also the freeway west of Köln is crowded.
- A1 between Wuppertal and Kamen is much more crowded after the adaption, with densities above 0.4 at many places.
- At Kamen, there is now not only a jam for people coming from Hannover, but also for people coming from the Ruhrgebiet.

Generally speaking, people "learn" according to the programmed rules to equilibrate the jams, i.e. fast ways around congested areas vanish.

5. Robustness results

One of the general questions of a simulation like this is how independent the results are from the specific set-up. For that reason, we tested several variations of the simulation.

Day-to-day variations of the general traffic jam patterns are low after day 15. As an example, Fig. 3 top shows the same situation as in Fig. 2 bottom one simulated day later.

Fig. 3. *Top:* Same as Fig. 2 (bottom), except that it is one "day" later. — *Bottom:* Same as Fig. 2 (bottom), except that the distance distribution is linear.

It has been reported from other traffic simulations that it is important how the individual agents remember past information. For example, a driver which only remembers the last instance of a trial of a route instead of some average performance may induce more oscillations into the system.[23] However, in the simulation setup as described here, using different memory rules did not lead to any noticeable difference in the simulations. The author's intuition is that the stochasticity of the underlying microscopic driving logic introduces already enough "fuzziness" into the system to avoid such oscillations. Traditional route choice models often bundle multiple drivers from the same origin to the same destination in one packet and do thus not allow for variability between these.[11]

Also, using a smaller bias towards longer distance destinations (Fig. 3 bottom, after adaption) does not change the overall traffic jam structure.

Obviously, it will be necessary to replace the arbitrary origin-destination-pattern of these simulations by more realistic data. Yet, some of the network bottlenecks seem generic with respect to transit traffic through NRW: Heavy traffic and congestion between Wuppertal and Kamen are well known, and, as one sees, a consequence of the missing extension of the freeway A4 beyond Olpe. This extension has since long been planned; but it leads through environmentally sensitive areas, and it is thus under discussion if it will ever be built. Note that the simulation methodology presented here can be used to evaluate the utility of such an extension, or what is needed to replace it by improvements along existing paths. Or, which traffic streams have to be reduced in order to manage with the currently existing infrastructure, and how this can be achieved.

The problems near Krefeld are due to the same bottleneck in North-East/South-West direction. It is also known that the Kölner Ring presents a bottleneck.

Ref. [19] contains more detailed descriptions.

6. Network throughput

As a quantitative measure, the accumulated number of cars which have reached their destination is counted as a function of time. Fig. 4 shows one result, for the fourth order distance distribution. Interestingly, the network performance *de*creases after drivers have learned. The probable explanation is that the network becomes crowded in a "balanced" way after drivers learn, whereas before, some parts are overcrowded and some are rather empty. It is, for example, reasonable to believe that, in Fig. 2 (top), a path from the south - westward around Köln - Wuppertal - Kamen - Hannover has higher throughput than in Fig. 2 (bottom). Refs. [15,24,25] contain other examples of unexpected or counter-intuitive behavior of traffic systems.

7. Discussion

Fig. 4. Accumulated number of cars which have reached their destination. "Days" 1 and 15 are shown. In day 1, all vehicles drive according to their geometrically shortest path, whereas in day 15 everybody has some knowledge of the travel time on different paths and usually chooses the fastest one. — Interestingly, the network throughput *de*creases during the relaxation, indicating that indeed something like grid-lock occurs not only in urban traffic, but can also occur in a freeway network.

The simulations of this paper use individual learning and route selection in a simulated traffic system. This produces a reasonable distribution of the traffic streams, given the initial origin-destination-assumptions. Thus, this method is capable to do the equivalent of the static equilibrium assignment[26] also for a dynamic and congested situation.

It cannot be expected that the simple assumptions yield a completely realistic picture of traffic streams; and for an exact comparison with reality no data was available. More realistic simulations are the topic of current work.[7,27] Nevertheless, it is perhaps astonishing that already such a simple model leads to a reasonable distribution of traffic streams. Moreover, the traffic patterns after adaption are robust against different statistical distributions for the origin-destination pairs, different learning rules, and different days. This supports the expectation that already relatively few information on realistic trip generation will yield rather realistic results.

Acknowledgments

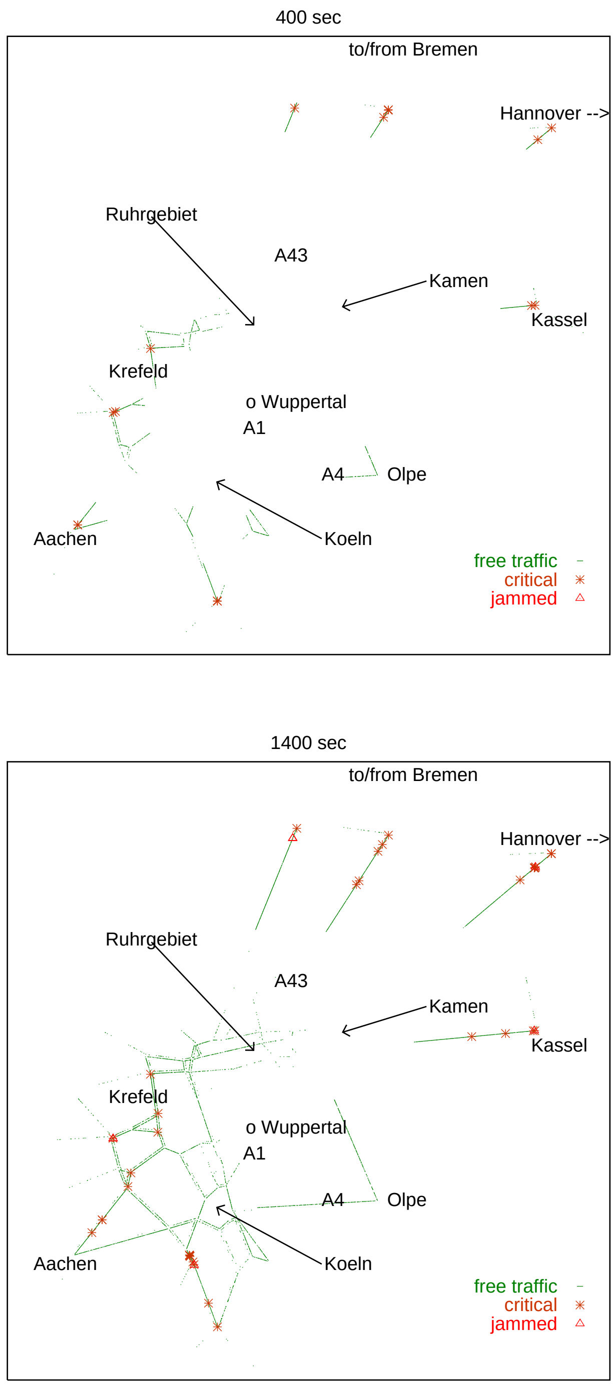
I learned using paths for traffic microsimulation from Chris Barrett, who had it already implemented in the demonstration version of TRANSIMS in 1992. Christoph Moll helped with the enumeration of the 10 shortest paths for each origin-destination pair.

References

1. K. Nagel and A. Schleicher, *Parallel Computing* **20**, 146 (1994).
2. M. Rickert, Master's thesis, University of Cologne, Köln, Germany, 1994.
3. M. Rickert and P. Wagner, *Int.J.Mod.Phys.C* **7**, 133 (1996).
4. M. Rickert, P. Wagner, and Ch. Gawron, in *Proceedings of the 4th PASA Workshop 1996* (in press).
5. G.D.B. Cameron and C.I.D. Duncan, *J. Supercomputing* (in press).
6. *TRAF user reference guide*, U.S.Department of Transportation, Federal Highway Administration, Publication No. FHWA-RD-92-060 (1992).
7. TRANSIMS, TRansportation ANalysis and SIMulation System, Los Alamos National Laboratory, Los Alamos, U.S.A. See http://www-transims.tsasa.lanl.gov.
8. M. Van Aerde et al., *INTEGRATION–Release 2 User's Guide*, 1995.
9. M. Van Aerde, B. Hellinga, M. Baker, and H. Rakha, INTEGRATION: An overview of traffic simulation features, *Transportation Research Records* (in press).
10. R.W. Hall, *Transportation Research C* **36**, 67 (1994).
11. R.H.M. Emmerink, K.W. Axhausen, P. Nijkamp, and P. Rietveld, *Transportation* **22**, 21 (1995).
12. H.S. Mahmassani, G.-L. Chang, and R. Herman, *Transportation Science* **20**, 258 (1986).

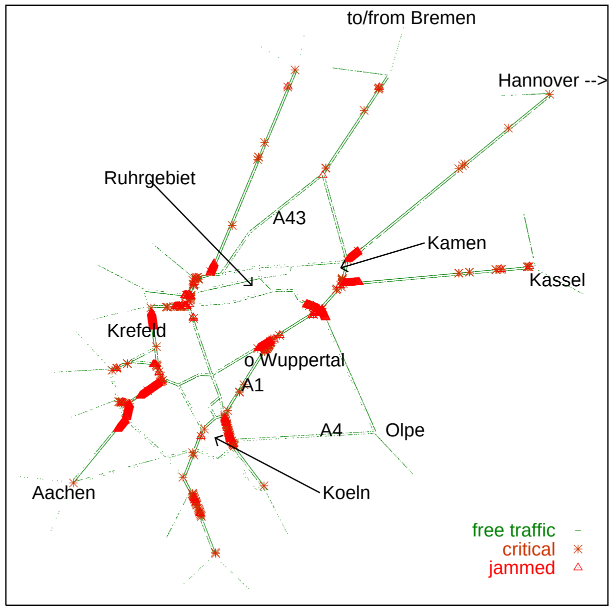
13. J.H. Holland, in *Lectures in the sciences of complexity*, ed. D. Stein (Addison-Wesley Longman, 1989).
14. W.B. Arthur, *American Economic Review (Papers and Proceedings)* **84** (1994).
15. T. Kelly, *Physica A* (in press).
16. K. Nagel and S. Rasmussen, in *Artificial Life IV: Proceedings of the Fourth International Workshop on the Synthesis and Simulation of Living Systems*, ed. R.A. Brooks and P. Maes (MIT Press, Cambridge, MA, 1994), p. 222.
17. K. Nagel, M. Rickert, and C.L. Barrett, Large scale traffic simulations, in *Proceedings of VECPAR'96* (in press).
18. C. Moll, personal communication.
19. K. Nagel, *High-speed microsimulations of traffic flow*, PhD thesis, University of Cologne, Köln, Germany, 1995.
20. E.L. Lawler, *Compinatorial optimization: Networks and matroids* (Holt, Rinehard, and Winston, New York, 1976).
21. K. Nagel, in *Physics Computing '92*, ed. R.A. de Groot and J. Nadrchal (World Scientific, 1993), p. 419.
22. K. Nagel and M. Schreckenberg, *J. Phys. I France* **2**, 2221 (1992).
23. K. Axhausen, personal communication.
24. J. Cohen and F. Kelly, *J. Appl. Probability* **27**, 730 (1990).
25. S. Catoni and S. Pallottino, *Transportation Science* **25**, 240 (1991).
26. Y. Sheffi, *Urban transportation networks: Equilibrium analysis with mathematical programming methods* (Prentice-Hall, Englewood Cliffs, NJ, 1985).
27. Forschungsverbund für Verkehr und Umwelt (FVU) NRW. See http://www.zpr.uni-koeln.de/Forschungsverbund-Verkehr-NRW/.

Nagel Fig. 1


400 sec
to/from Bremen
Hannover -->
Ruhrgebiet
A43
Kamen
Kassel
Krefeld
o Wuppertal
A1
A4
Olpe
Aachen
Koeln
free traffic
critical
jammed
1400 sec
to/from Bremen
Hannover -->
Ruhrgebiet
A43
Kamen
Kassel
Krefeld
o Wuppertal
A1
A4
Olpe
Aachen
Koeln
free traffic
critical
jammed

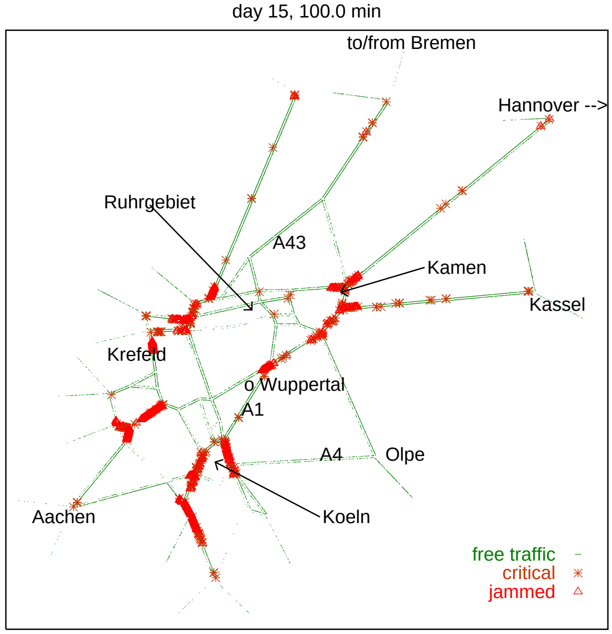
Nagel Fig. 2

day 1, 100.0 min



4th order

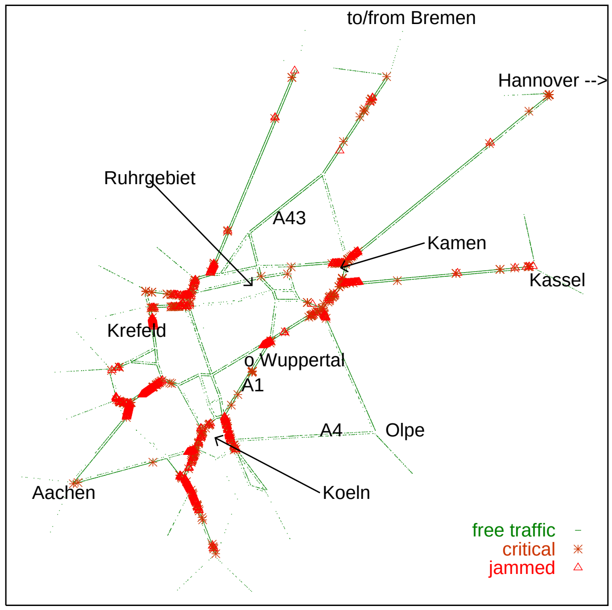
day 15, 100.0 min



4th order

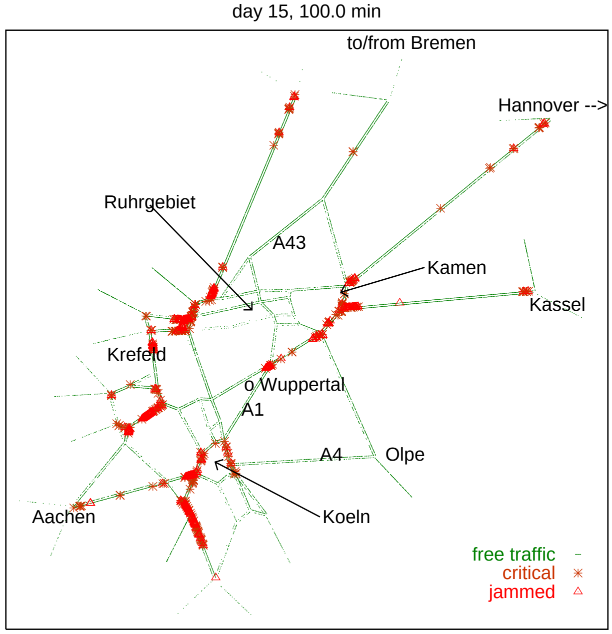
Nagel Fig. 3

day 16, 100.0 min



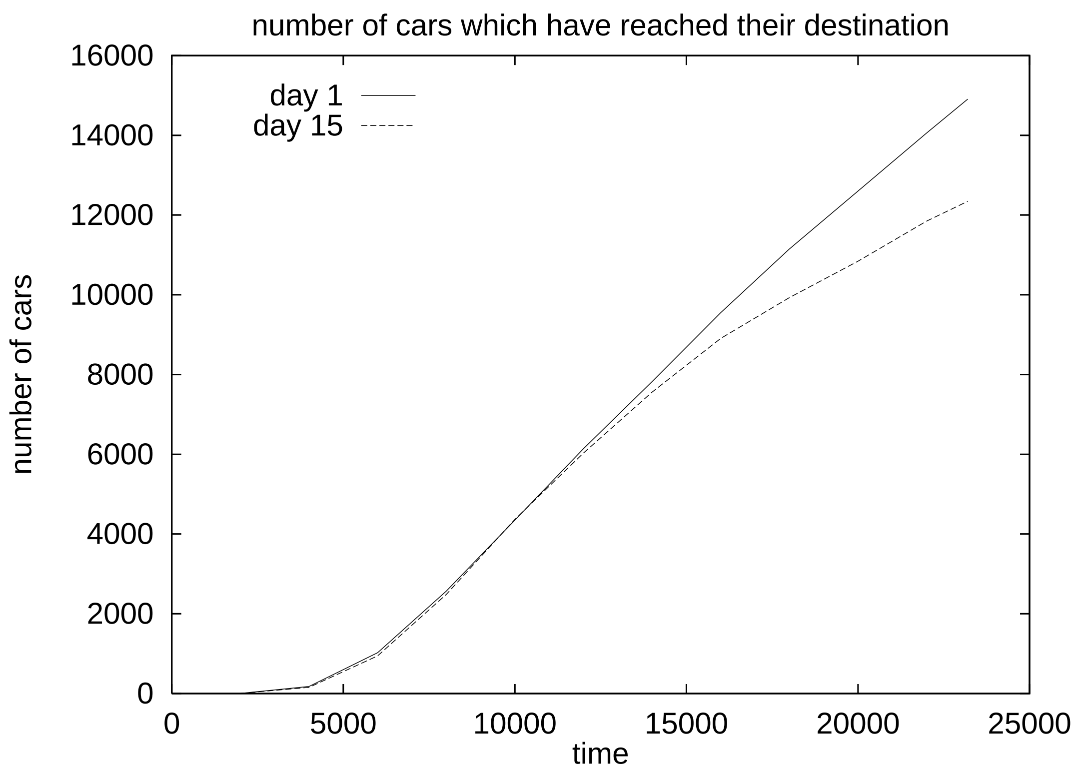
4th order

day 15, 100.0 min



linear

Nagel Fig. 4


number of cars which have reached their destination
day 1
day 15
number of cars
time
16000
14000
12000
10000
8000
6000
4000
2000
0
0
5000
10000
15000
20000
25000